

ARIZONA DEPARTMENT OF TRANSPORTATION

REPORT NUMBER: FHWA-AZ88-801

FLOOD FREQUENCY METHODS FOR ARIZONA STREAMS

State of the Art

Final Report

Prepared by:
Brian M. Reich
Consulting Engineer
2635 East Cerrada Adelita
Tucson, Arizona 85718

October 1988

Prepared for:
Arizona Department of Transportation
206 South 17th Avenue
Phoenix, Arizona 85007
in cooperation with
U.S. Department of Transportation
Federal Highway Administration

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Arizona Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation. Trade or manufacturers' names which may appear herein are cited only because they are considered essential to the objectives of the report. The U. S. Government and The State of Arizona do not endorse products or manufacturers.

TECHNICAL REPORT DOCUMENTATION PAGE

1. REPORT NO. FHWA-AZ88-801		2. GOVERNMENT ACCESSION NO.		3. RECIPIENT'S CATALOG NO.	
4. TITLE AND SUBTITLE STATE OF THE ART FLOOD FREQUENCY METHODS FOR ARIZONA STREAMS				5. REPORT DATE October 1988	
				6. PERFORMING ORGANIZATION CODE	
7. AUTHOR(S) Brian M. Reich				8. PERFORMING ORGANIZATION REPORT NO. ATRC/001	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Brian M. Reich, Consulting Engineer 2635 E. Cerrada Adelita Tucson, Arizona 85718				10. WORK UNIT NO.	
				11. CONTRACT OR GRANT NO. HPR-PL-1(31) Item 801	
12. SPONSORING AGENCY NAME AND ADDRESS ARIZONA DEPARTMENT OF TRANSPORTATION 206 S. 17TH AVENUE PHOENIX, ARIZONA 85007				13. TYPE OF REPORT & PERIOD COVERED Final Report April 1987 - October 1988	
				14. SPONSORING AGENCY CODE	
15. SUPPLEMENTARY NOTES Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration					
16. ABSTRACT This report discusses various aspects of previous, present and future methodologies for flood frequency analysis. Means for developing estimates of flood peaks that have specified rare probabilities of occurring at gaged stream sites are described. Problems and means of estimating design flood at ungaged sites are described, including need for new short duration rainfall intensities. Emphasis on arid zone difficulties and promising new approaches are stressed. A strategy for executing the data analysis and presentation of a design manual to practicing engineers and hydrologists is presented. Manpower, time and budget requirements are estimated.					
17. KEY WORDS arizona, flood frequency, peaks, estimates, changes, plotting, regression, confidence, gaging, watersheds, deterministic runoff methods			18. DISTRIBUTION STATEMENT Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161		
19. SECURITY CLASSIF. (of this report) Unclassified		20. SECURITY CLASSIF. (of this page) Unclassified		21. NO. OF PAGES 56	
				22. PRICE	

PREFACE AND ACKNOWLEDGEMENTS

The objective of this report is to present and discuss various aspects of previous, current, and future methodologies for flood frequency analysis. Means for developing estimates of flood peaks that have specific rare probabilities of occurring at gaged stream sites are discussed. The problems and means of estimating design floods at ungaged sites are described, with emphasis on arid zone difficulties and promising new approaches. A strategy for executing the data analysis and presentation of a design manual to practicing engineers and hydrologists is presented, along with manpower, time and budget requirements.

The study was financed by the Arizona Transportation Research Center (ATRC), Arizona Department of Transportation. The research team would like to acknowledge the cooperation and support of Mr. Frank McCullagh and Mr. Ottozawa Chatupron of ATRC during the study.

TABLE OF CONTENTS

	Page
LIST OF FIGURES.....	iv
LIST OF TABLES.....	v
ACRONYMS	vi
I. EXECUTIVE SUMMARY.....	1
I.1 Time & Production Schedule.....	4
I.2 Pre-overhead Budget, Staffing & Time Needs.....	5
I.3 Library Work Completed.....	7
II. ESSENTIAL CHANGES.....	7
II.1 Pre-test for Changing Flood Regimes.....	7
II.1.1 Graphical Stationarity Test.....	9
II.1.2 Statistics Increase With Floodplain Development.....	10
II.2 Pooling All Watershed Sizes Is Inappropriate for Arizona.....	11
II.3 Importance of Small Area Floods & Danger of Extrapolating From Larger Streams.....	15
II.4 New Rainfall Probability Atlas Essential.....	16
II.5 Deterministic Model for Rare Floods on Small WS...	17
II.6 Input from Other Sciences for Flood Region Delineation.....	19
II.7 Compendium of Flood History & Frequency Graphs....	19
II.7.1 Computerize Credibility Check of At-Site Q100 Estimates for Busy Practitioners.....	20
III. PRACTICAL ASPECTS OF FLOOD FREQUENCY ANALYSIS.....	24
III.1 Confidence Bands.....	25
III.1.1 State Specified Confidence Levels Worth Consideration.....	28
III.2 USGS Contributions.....	29
III.3 ARS Walnut Gulch Data and Research.....	30
III.4 State Should Boost Gaged Urban Watersheds.....	31
IV CONCLUSIONS.....	33
REFERENCES.....	35

LIST OF FIGURES

	Page
1. Flowchart of Research Tasks & Delivery Schedules for Six Work Products.	39
2 Chronological Series of Floods Observed at Congress Street.....	40
3. Graphical Non-stationarity Test Shows Floods in Recent 25 Years Are Far Bigger Than Those in the Earlier Record.....	41
4. Scatter of LP3-Q100's, in Log Units, After USGS Applied 1987 Stochastic Methods to Watersheds In and Around Pima County.....	42
5. Tight Regression Between A and "Best Eye-Fit" Q100 On 10 Small WG Watersheds and Its Relationship to USGS Q vs A Curve from 49 Sites of All Sizes Throughout a Larger Region.....	42
6. Scatter of Pima County "Best Eye-Fit" Q100 From 48 USGS Gaged Watersheds Spread Throughout Southeastern Arizona.....	43
7. Twenty-year old Example of Graphical FFA's That Showed Users How Differently Each Stream Was Fitted By Three Statistical Distributions.....	44
8. Flood Series Plotted on Three Probability Papers & One Student's "Best Eye-fits" to Determine Q100.....	45
9. Example of Widely Separate LP3 Curves from Three 17-year Segments of a 42 sq. mi. Watershed.....	46
10. Spread Between Flood Estimates from Two 29-year Segments was Smaller With Gumbel's EV Than With LP3 Mathematical Fitting.....	46
11. Hypothetical Example of Chow's Confidence Bands About the EV Central Tendency.....	47
12. Computer Output from LP3 Can Give Strange Estimates if Outlier or Regional Skew Problems Arise.....	48

LIST OF TABLES

	Page
1. Hypothetical Budget for 3-year Phased Development.....	5
2. Changes in Mean of Observations and Two Estimates of Q100 for Three Separate Thirds of Tucson's Santa Cruz Flood Record.....	11
3. Plotting Paper Preferences Among 31 Eye-fitters, with Average and Range of Q100 Estimates.....	22
4. Results from Five Different Mathematic Models.....	24

ACRONYMS

A	Watershed Area
ARS	Agricultural Research Service
CFA	Consolidated Frequency Analysis for multiple distributions on PC, Environment Canada
DRM	Deterministic Runoff Model
EV	Extreme Value
FFA	Flood Frequency Analysis
GEV	Generalized Extreme Value distribution, used in Great Britain and included in CFA
GSL	Generalized Least Squares
LEV	Log Extreme Value
LN	Log Normal
3LN	Three-parameter Log Normal, a flexible structured distribution
LP3	Log Pearson Type III, Curve fitting procedure recommended in 1967 by WRC
PC	Personal Computer
Q100	Flood peak estimated for 100 year return period
Q	Design peaks estimated for another return period
QBAR	Mean of the series of observed floods
Q vs A	Relationship Between Design Floods and Watershed Areas, and Other Factors
SEE	Standard Error of Estimate
USGS	United States Geological Survey
WG	Walnut Gulch
WRC	U.S. Water Resources Council

I. EXECUTIVE SUMMARY

New flood estimators are needed for highway design and maintenance. Within the last decade Arizona has experienced many floods that far exceeded maxima measured before our last statewide study began (1) [Roeske, 1978]¹. Arizona is enjoying accelerated community growth, within a litigious era of burgeoning interactions between floodplain users and highway drainage structures. Excessive over- or under-design can be costly. Old estimates of flood potential no longer adequately represent this natural hazard on many streams.

Fortunately additional years' records have accumulated over more than ten years since the last statewide analysis was initiated. Moreover, significant advances have occurred in the fitting of statistical distributions to annual maximum flood series. Re-analysis is needed to insure that future highway drainage structures and corrective measures take account of recent data and current methods.

At-site analysis will follow the Water Resources Council (WRC)² Bulletin 17B (2) [WRC, 1982]. This does not simply imply the rote application of the Log Pearson Type III (LP3) computer program. U.S. Geological Survey (USGS) and other stochastic hydrologists have developed improved methods recently. The Canadian government distributes a versatile, modern program (3) [Pilon, Condie, Harvey; 1985] for a personal computer (PC). It was approved by the Chief of the Hydrology Division, of the USGS.

¹ Citations are listed by numbers under "References." Within the text, authors and year of publication have been added within square parentheses, for the reader's convenience.

New analysis may show that the high standard errors of estimates (SEE), for which the USGS have been criticized, were partially the result of LP3's poor fitting of individual at-site flood series. Hopefully the, now permitted, replacement of LP3 with another more suitable statistical distribution may reduce SEE's and produce better extrapolation to ungaged sites. The Canadian computer program "Consolidated Frequency Analysis" (CFA) includes LP3, the generalized extreme value (GEV), the three-parameter log normal (3LN) and other options for at-gage analysis.

The next step in developing flood estimators for use at ungaged sites, is the researcher's development of relationships between at-site estimates like Q100 and watershed parameters. The classical relationships between design off-gage peaks (Q) and watershed area (A) are involved. This phase of developing design off-gage flood estimators has also been enhanced by new research achievements of a few federal and academic stochastic hydrologists. This project should also use field sciences, and consideration of physical factors affecting floods.

A literature search and discussions with deterministic runoff modelers (DRM) suggest an additional way of improving flood estimates on small watersheds in Arizona. DRM invokes equations of overland and channel flow with infiltration across a watershed in order to estimate the size of each flood from any causative rainstorm. Arizona's sparsity of large flood-producing storms suggests that statistical regression equations may need to be supplemented by DRM. Thus synthetic generation of design size floods and series on ungaged sites could overcome our data

deficiency. It may signal the path needed to reduce the excessive SEE's previously plaguing Q vs. A studies.

Much has been happening in various federal agencies, in universities, in Arizona communities, in other states, and overseas. Today Arizona's local and various State agencies employ many expert hydrologists. Their indulgence is sought for the colloquial style and use of graphical illustrations which follows. A few real cases have been selected to illustrate characteristics of flood series. Some are peculiar to semi-arid regions. Others were selected to explain general techniques in flood frequency analysis (FFA). Over four hundred books, reports and journal articles on both practical and esoteric matters were collected and reviewed. Thirty nine of them are included under References to cover the main themes discussed. This State-of-the-Art Study is intended for a broad audience, and aims to update understanding of practical FFA aspects of concern to highway hydraulic engineers.

In addition to the usual flood predictors, the proposed research should also provide the design community with two useful products, not previously available. The first would be a statewide report on possible localized increases flood potential. Such so-called "non-stationarity" could be discerned in long gage histories. The second addition will be a publication containing two pictures for each gaged record. One will display the chronologic series of floods. The other will plot these on probability paper and show appropriate frequency curves and design values.

In summary, highway hydraulic engineers and other state, county, and city agencies will benefit from a new flood frequency analysis (FFA) for Arizona. This assumes that flood studies are executed concurrent with or after new short-duration rainfall-intensity probability studies for Arizona.

I.1 TIME & PRODUCTION SCHEDULE

A plan to meet the objectives mentioned in Problem Statement HRP-PL-1(31), Item 801 of 3-25-1987, may involve 22 research elements interconnected as in Fig. 1. References to that figure will be by numbers which appear towards the upper right of its rectangles or diamonds. Interactions between these study segments will result in a sequence of six research products, numbered at the upper left of each parallelogram depicting these. The first of these would be available to practitioners in 15 months. The second publication could be completed within another 3 months. The next two products could follow at six-month intervals. The two remaining products will be completed at the end of the project.

The following outcomes can be expected :

- 1) the first statewide report on long-term flood changes;
- 2) a compendium of annual maximum floods measured at about three-hundred Arizona and nearby sites will be presented; first numerically as tables, then as untransformed chronological plots, and then as observations superimposed on various probability curves;
- 3) discuss geomorphic and hydrometeorological flood regions for large unregulated watersheds;
- 4) conventional, regression estimators for intermediate watersheds;

- 5) conventional flood estimators for watersheds smaller than about 10 square miles;
- 6) quantitative test of potential rainfall-runoff models as tools for improving flood peak estimators for small watersheds. If funding constraints will not allow execution of blocks 17 through 22, this product could be investigated in another project.

I.2 PRE-OVERHEAD BUDGET, STAFFING & TIME NEEDS

Consideration of work needed to accomplish the 28 elements depicted in Fig.1 led to the approximate budget shown in Table 1.

Table 1. Hypothetical Budget for 3-Year Phased Development

<u>Direct Labor (Including Fringe Benefits)</u>	<u>Person-Months</u>	<u>Dollars</u>
Director & Flood Frequency Specialist	24	130,000
Stochastic Hydrology Specialist	3	15,000
Hydrometeorology Specialist	2	10,000
Geomorphology Specialist	1	5,000
6 Part-time Graduate Students or 3 full-time Technicians	100	100,000
Secretarial	24	30,000
Sub-total labor plus benefits		290,000
<u>Other Expenses</u>		
Consultant in Programming		4,000
Computer & Other Services		6,000
Communications		8,000
Travel		8,000
Supplies		5,000
Publications		6,000
Sub-total		37,000
<u>Equipment</u>		
Personal Computer, Software & Plotter		10,000
Copier		1,000
Map Measuring, Digitizing & Drafting Equipment		2,500
Map & Document Storage Cabinets		1,500
Sub-total		15,000
TOTAL		342,000

This estimate does not include indirect costs. Overhead charges can be as little as 15% for a state university, when only state funds are involved. This would bring the total to \$393,000. If federal pass-through funds are involved, the rate is 46.3%, bringing the total to \$499,000. The pre-overhead budget for products 1 through 5 could drop to about \$300,000.

A team considered appropriate for the interdisciplinary project should comprise engineer/scientists, familiar with each other's related research and who have had prior professional interaction. Together their experience should range from understanding statistical concepts, through quantitative knowledge of rainfall/runoff systems, to a displayed interest in communicating with various levels of government and consulting engineers. Their skills should include flood frequency analysis (FFA), deterministic runoff modeling (DRM), stochastic hydrology, hydrogeomorphology, hydrometeorology of floods and practical experience. Familiarity with Arizona's flood processes is a prerequisite. It will also be helpful if the contractor has early knowledge as the upcoming revision of the storm rainfall probability atlas, during its preparation.

Over the three year project, the Principal Investigator must devote 24 her/his-months to this project. Besides managing the project, and coordinating efforts of three other senior scientists, she/he shall personally direct three of the technicians or graduate students, and shall complete all reports. The other three subject specialists should devote six person-months supervising their workers in two years.

I.3 LIBRARY WORK COMPLETED

Over four hundred articles and reports were reviewed. By the time a contract is let more will be available. The small subset of 39, listed under **References**, contains the backup details on major topics and suggestions for an Arizona study.

II. ESSENTIAL CHANGES

Analytical techniques should differ significantly from those used in our previous USGS studies (1) [Roeske, 1978], (4) [Eychaner, 1984]. Some of the major needed changes are described in the following subsections. Many of the suggestions are additional to approaches mentioned in a 24-page USGS Proposal for southwestern flood research (5) [Wahl, 1987] presented to the FHWA Tri-regional Hydraulics Conference in Salt Lake City in June 1987.

II.1 PRE-TEST FOR CHANGING FLOOD REGIMES

A key assumption in performing a flood frequency analysis (FFA) is that "in general, an array of maximum peak flow rates may be considered a sample of random and independent events" (2) [WRC, 1982]. Previous Arizona analysis did not validate this assumption before fitting a statistical distribution to each station's series of observations to estimate the 100 year flood (Q100), etc.. Communities which have experienced rapid floodplain development and have needs for bridge construction and channelization will gain long-term benefits if this WRC requirement is adhered to in the next FFA study.

Tucson had a bad experience because the statewide (1) [Roeske, 1978] and south-eastern Arizona (4) [Eychaner, 1984] studies did not follow national guidelines (2) [WRC, 1982]. Prior to 1960 the largest Santa Cruz River flood at Congress Street was 15,000 cfs which occurred in 1914. This flood was exceeded on two occasions in the 1960's, once in the 1970's with 24,000 cfs. In 1978 Pima County notified federal agencies that the 64-year flood record appeared non-stationary. A flood of 53,000 cfs in October 1983 inflicted considerable damage on Tucson, because little protection was available beyond the 30,000 cfs, which was used for Q100 to prepare Flood Insurance Administration maps. The 53,000 cfs event was twice the magnitude of the 500-year flood estimated by log Pearson III (LP3) analysis based on the 61 years of record starting in 1914 (1) [Roeske, 1978].

A chronological plot of the flood history, shown in Fig.2, has convinced many laymen that big floods have become bigger and more frequent in modern times. Using LP3 on the 1914-1959 data would have estimated Q100 as 20,000 cfs. The same method applied to data from 1960 through 1984 estimates Q100 as 50,000 cfs. The earlier Q100 estimate would correspondingly be accorded a return period of 10 year, on the recent 25 year's data only. A 50,000cfs estimate on the earlier 45-year LP3 computation would have been called a 100,000 year flood (6) [Reich & Davis, 1986]. In fact a Log Extreme Value (LEV) statistical distribution fits the data best and estimates today's Q100 as 96,000 cfs. This higher flood regime has been associated with the entrenchment of

main channel and tributary systems within the geological floodplain and connected tributary systems shortening travel times. Thus flood-producing rains, which do not appear to have increased, now result in hydrographs which are more spiked (7) [Reich, 1985]. A pre-test should be run to established whether similar changes in flood behavior are occurring elsewhere.

Bulletin 17B states that, "Only records which represent relatively constant watershed conditions should be used for frequency analysis." It also states: "Man's activities which can change flow conditions include urbanization, channelization, levees, construction of reservoirs, diversions, and alteration of cover conditions. Special efforts should be made to identify those records which are not homogeneous." Including earlier data from a more pristine watershed into a frequency analysis violates this stationarity requirement.

The upcoming ADOT work should ensure adequate, understandable, stationarity test on all flood series exceeding 35 years before proceeding to estimate Q100, etc...

II.1.1 GRAPHICAL STATIONARITY TEST

A visual means of examining whether floods from two different periods of a record were produced by the same hydrologic mechanism is to plot both segments on one sheet of probability paper (Fig.3). The floods from 1915-1959 are shown as x's. The record from 1960-1984, indicated by dots, plots substantially and consistently above the earlier data set. It is most unlikely that these distinctly differing flood frequency

arrays were generated by random chance. This graphical portrayal is even more meaningful than a non-parametric statistical test, which does not arrange the two series at different return periods. The Kruskal-Wallis non-parametric test showed that there is only a 7.2% chance that the disproportionate number of bigger recent floods occurred simply by chance. The visual test makes a far stronger argument than does statistical jargon concerning null hypotheses or significance levels. This procedure warrants a computer program (8) [Reich & de Roulhac, 1985] in order to select an optimum beginning for the "current" flood regime.

II.1.2 STATISTICS INCREASE WITH FLOODPLAIN DEVELOPMENT

Dividing Tucson's Santa Cruz series of flood peaks into three virtually equal segments allows the comparison of averages, coefficients of variation, skewness of observed floods, and Q100's. Two statistical distributions were also fitted to each data set to determine Q100 by LP3 and by LEV methods. If the flood regimen had not changed one would have expected some of the statistical parameters for earlier years to have been greater, simply by chance. Table 2, however, shows all to increase somewhere after the 1950's.

Table 2. Changes in Mean of Observations and Two Estimates of Q100 for Three Separate Thirds of Tucson's Santa Cruz Flood Record.

Record Segment	Geometric Mean	Q100 Estimates (cfs)	
		LP3	LEV
1915/37	4,337	22,000	42,000
1938/61	5,466	20,000	37,000
1960/84	6,776	54,000	96,000

Another statistical parameter that influences flood prediction is the variance of the annual maxima. Increased variance steepens a flood frequency line. Variance is also higher in the last 25 years. A statistical f-test suggests that there is only a 6% chance of this occurring randomly.

II.2 POOLING ALL WATERSHED SIZES IS INAPPROPRIATE FOR ARIZONA

Another change that should be implemented if a new FFA is undertaken concerns the second phase, involving relationships between Q100 on different watersheds. After settling upon all at-gage flood estimates in Product 2, the researcher must start towards regression studies denoted in Blocks 14, 15, and 16 of Fig. 1. The previous studies (1) [Roeske, 1978], (4) [Eychaner, 1984] combined Q100 estimates from watersheds (WSs) over 5,000 sq. mi. with those of area less than 1/6 sq. mi. Combining point estimates of flood peaks for any design frequency (Q), from such a wide range of watershed sizes (A) into a single regression set overlooks the diverse processes that occur as desert floods

propagate downstream. Floods on small headwaters result from local summer rains of high intensity and very short duration. Large watersheds flood in the autumn or winter when persistent, low-intensity rains cover wide areas. The duration of winter storm rainfalls that are causally related to large watershed Q 's may be 12 hours or longer. Regressable rainfall intensities for small watersheds will probably be as short as 15 minutes, usually occur in the summer, and are unrelated to long rains. So flood magnitude will not regress against either long or short duration when large and small watersheds are pooled into one sample.

Q 's from intermediate sized watersheds are influenced by other factors. They are decreased by channel abstractions which increase as watersheds become larger than about 1 or a few more square miles. Depending on geomorphic settings Q vs. A relationships may switch as different threshold is passed. Feedback arrows among Blocks 10 through 16 of Fig. 1 suggest cluster analysis may discover the most appropriate sizes for grouping watersheds, with the object of strengthening each subgroup's regression relationship. Size stratification alone may need to be supplemented by qualitative terrain knowledge in order to improve Q vs. A predictors. Hydrometeorological regions and geomorphic provinces provided effective flood stratification in Pennsylvania (9) [Reich, King & White, 1971], (10) [Aron, et al., 1981], (11) [Morton, 1981].

Recent refinements in stochastic hydrology, working on watersheds pooled across the wide range of A are not expected to prove a panacea in the desert. An example is contained in a USGS

manuscript (12) [Tasker, Eychaner, & Stedinger, 1987] concerning 89 gages in or near Pima County. The new generalized least squares (GSL) proved only slightly better than the ordinary least squares (OSL) method in relating Q100 to A. Fig. 4 is taken from that manuscript. It shows a prediction curve which at one unit of drainage area estimates Q100 as 2,190 cfs. Data points in that vicinity spread from 700 to 10,000 cfs. Natural logarithms are somewhat cumbersome for earthlings to visualize. Apparently the watersheds ranged from 0.15 to 4,471 square miles. Scatter of Fig. 4 LP3 estimates are very large compared to what was achieved with only ten gages, all located within less than 60 square miles. These had been prepared in response to a USGS request for a review (13) [Reich, 1978] of an earlier manuscript.

Minimal scatter (Fig. 5) resulted when only 10 small Walnut Gulch (WG) gages were used. "Best eye-fitted" Q100's (14) [Reich & Renard, 1978] had been estimated for ten gages within the 58 square mile rangeland experiment station, near Tombstone in southeastern Arizona. It is not surprising that they fall so closely to the WG curve:

$$Q100 = 2,000 A^{.892 - .232 \log A} .$$

These watersheds have much in common regarding climate, geology, soils and land use. The dates of individual annual maxima dates, however, were surprisingly independent of each other at the ten different gages. Annual maxima occurred on

different days in response to separate, small, intense thunderstorms.

Simply for discussion, the USGS's "Aldrich-Eychaner" June 1978 curve was added to Fig. 5. It actually represented 48 LP3 Q100 estimates on USGS gages across 26,000 sq. mil of southeastern Arizona, which contained WG. Only the part of this Aldrich-Eychaner curve below 60 square miles can be compared to the WG curve in Fig. 5.

The County's review study, which the USGS requested in 1978 also applied the same "best eye-fit" on EV, LEV, and LN paper as had been used to develop the WG curve. Fig. 6 shows the scatter among the 48 USGS WS's smaller than 60 square miles. Stations, from 26,000 square miles of southeastern Arizona can be expected to scatter widely from the WG curve. Ideally one may conceive of a set of curves somewhat parallel to the WG and/or Aldrich-Eychaner templates. Some of the watersheds in Fig. 6, represented by dots, must possess very different flood-producing features than the others.

Unfortunately there is also random error in the Q100 estimates, which also accounts for some of the dot's scatter. Fortunately many extra years of data have accumulated at some gage-sites. Careful restudy must strive to produce better flood estimators in Products 3, 4, and 5 of Fig. 1. In the meanwhile, engineers may be more comfortable if using the WG curve, or some higher envelope than the Aldrich/Eychaner central tendency regression to the dots in Fig. 6.

The greater lesson from this subsection is the urgent need to simultaneously pursue applications of deterministic runoff modeling. The feasibility study (Blocks 17 through 22 in Fig. 1) could conclude that deterministic runoff models (DRM) offer improvements beyond what can occur with the more conventional Q vs. A regressions of Products 3, 4, and 5.

II.3 IMPORTANCE OF SMALL AREA FLOODS & DANGER OF EXTRAPOLATING FROM LARGER STREAMS.

Small watersheds concern the majority of highway drainage designs. They are diverse and can be expected to possess very high or very low flood potential in certain cases. They are also seldom gaged. For example, within the United States 846,000 tributaries with areas between 1 and 2 sq. mi. were represented by less than 60 stream gages (15) [Guisti, 1963]. Only 10% of Arizona's gaged streams have watersheds smaller than 1 sq. mi. It is difficult to adequately sample their wide range of flood producing factors within Arizona's three major hydro-climatological zones (16) [Hirschboech, 1982]. Watersheds of twenty square miles or more are a composite of many smaller tributaries. Smaller subareas differ from each other regarding slope, infiltration, land-use and other flood-producing properties. One small design may contain all the high runoff properties. Extrapolating larger watersheds response is a dangerous surrogate. It may lead to underprediction, because slopes frequently increase as watershed's get smaller. Absence of steeper watersheds from a sample would suppress the importance

of that factor in attempted regressions. A smaller watershed any also stand a high chance of being entirely covered by the heart of high intensity rain. Small watershed floods are different in many other ways. Watersheds from 5 to 10 sq. mi. are usually devoid of rain over half their extent during a flood-producing storm that deposits about 3 inches in less than half an hour elsewhere within it. Short flood histories in the desert stand a small chance of including critical flood conditions like heavy rain concentration near the outlet. Given the number of highway structures requiring Q estimates small watersheds warrant more attention than they received in past flood studies, at the tail of a large-watershed sample.

II.4 NEW RAINFALL PROBABILITY ATLAS ESSENTIAL

Previous regression attempts (1) [Roeske, 1978], (4) [Eychaner, 1984] were unable to relate flood peak estimates to rainfall probability intensities. It appears that the "Precipitation Frequency Atlas of the Western United States" (NOAA2) (17) [Miller, Frederick, & Tracey, 1973] may have been partly responsible. The latter did not have adequate short-duration data to use. Hopes of relating flood estimates, like Q_{100} or Q_{10} , should not be abandoned, however. A recent state-of-the-art study (18) [Reich, Brazel, & Clark, 1987] outlines how a new rainfall probability atlas could be prepared within two years. Hopefully this new atlas will yield improved short duration storm estimates and their variation across Arizona.

Rainfall intensity may become an effective independent variable accounting for some statewide flood variability.

It may be possible that some elements of a rainfall study and of a flood study may run concurrently. Flood studies should not proceed beyond Product 1 before new rainfall estimates are available. The two projects should be planned together and run concurrently.

II.5 DETERMINISTIC MODEL FOR FLOODS ON SMALL WS

Heavy flood-producing storms are infrequent and widely scattered in Arizona. Most of our stream gages do not capture more than two or three floods within the design class. The dilemma may be resolved by recently developing technology. Deterministic runoff modeling (DRM) can be used in the synthesis of floods generated from hypothetical rainstorms. Examining such flood peaks generated from a spectrum of design-size rains upon typical watersheds warrants investigation. Researchers (19) [Woolheiser, 1986] have noted the sensitivity of flood peaks to rainfall rates for various short durations. The Agricultural Research Service (ARS) developed the KINEROS computer model. It simulates hydrographs from infiltration, ponding, kinematic routing of overland flow across a cascade of planes and channels in southeastern AZ.

Highway engineers need to know if the DRM approach can work elsewhere. The ADOT project should test it against small watersheds in central Arizona. If successful this could yield an enhancement to the classical flood versus area (Q vs. A) method,

which needs more long records containing numerous design-size observations than are available from the USGS network. Block 17 of Fig. 1 calls for simulations to be performed in untest USFS gages watersheds Arizona.

Block 18 transposes existing scientific information into the user mode. Block 19 will require stochastic input of storm durations and intensities, to be made from the new rainfall atlas. Enough simulations must be run to indicate the sensitivity of flood peaks to realistic ranges of A, slope, soil, tributary configuration, etc.. Rainfall affecting small watersheds throughout Arizona would only be run in another project, dependent on this pilot investigation. Block 22 will compare Q100 from large synthesized floods to Product 5, which represents the best possible from recorded floods.

Block 17 should be commenced simultaneously with Block 1. Completion through Block 21 will be time consuming. Initiation of comparison 22 should start by the 33rd month of the project. This 6th Product will determine the potential utility of DRM synthesis. It will show whether the Q vs. A approach is adequate or can be enriched by DRM synthesis.

Product 6 has an important confirmatory role. It will indicate whether the poor sampling of diverse small WSs and short gage records are preventing classical FFA from giving Arizona's design community realistic Q100 estimates.

II.6 INPUT FROM OTHER SCIENCES FOR FLOOD REGION DELINEATION.

Hydrometeorological settings across the state, as well as geomorphic types, of the flood producing features of gaged watersheds deserve serious study. They can enhance our understanding of regional flood variations. Methodology still needs to be developed for Arizona to incorporate these qualitative inputs along with the feedback loops suggested in Block 10 through Block 16. Three person-months from experts' to supervise technicians working on these non-quantifiable influences for 18 months is budgeted.

II.7 COMPENDIUM OF FLOOD HISTORY & FREQUENCY GRAPHS

A team of flood hydrologists, with considerable experience in FFA and understanding the physics of floods in semi-deserts, will synthesize various evidence to find the appropriate frequency curve for each watershed. After consulting with the sponsor the project shall publish its 2ND PRODUCT. Fig. 7 shows the format of an equivalent volume (20) [Reich, 1969] prepared 20 years ago. Recent advances in FAA and computer graphics will greatly enhance the compendium.

In addition to numerical tabulation of observed floods, and selected design estimates, a graphical compendium of site-specific flood frequency curves can be published within 18 months of project initiation. Graphical depiction of at-gage flood behavior would give users a far clearer impression of reliability than they get from standard errors of estimates.

II.7.1 COMPUTERIZED CREDIBILITY CHECK OF AT-SITE Q100 ESTIMATES FOR BUSY PRACTITIONERS.

An unfortunate practice of not publishing graphical probability plots for each gage-site has crept into recent regional flood frequency analysis. Instead, readers presently receive an appendix containing estimates produced by the preselected statistical model for: 2-, 5-, ..., 100- or 500- year return periods. Some stochastic hydrologists simply list the mean, standard deviation, skewness, or kurtosis. None of these contain as much information as do the observed floods, rearranged in order of magnitude on three or more types of probability paper. Floods can be ranked and plotted on an array of probability papers by a personal computer (21) [de Roulhac, 1987]. With a minimum of instruction, the engineer or hydrologist could fit a straight line representing the larger half of the observations, in which the designers' interest lies. Eye-fitting a straight line through one set of annual maximum floods is shown in Fig. 8.

The questions which arise are: "Are there big differences in the Q100's estimated by different people? Do individual preference among the three popular distributions influence outcomes?" The answer to both are negative. A test (22) [Reich, 1980] showed how close together estimates of Q100 were among 31 students who independently applied this "best eye-fitted" flood frequency analysis to a 58 square mile Arizona watershed. Data comprised annual peaks observed at a laboratory-calibrated self-cleaning flume in southeastern Arizona. The largest and smallest

Q100 estimates obtained by the students were 9,200 and 7,000 cfs for this visual test. In contrast, five common mathematical models estimated Q100 from 5,540 to 60,870 cfs for the same flood series.

The students in this introductory hydrology course were given four hours of instruction in statistical fundamentals and graphical FFA. Their first task was to plot the observed floods according to :

$$Pe = \frac{m - 0.4}{N + 0.2}$$

where Pe = probability of each annual maximum observed,

m = order of magnitude of the flood from the largest,

N = number of years of record.

This plotting position formula was proved (23) [Cunnane, 1978] to be theoretically sound for EVm LEV and LN paper. The 31 students had little thought they would each obtain radically different estimates of Q100. They mistrusted human judgment at fitting a straight line. Which of the 3 papers was best?

Independent judgments, summarized in Table 3, were surprisingly similar. Two-thirds of the analysts chose EV paper as most appropriate, because half the floods plotted close to a straight line. The largest, the average, and the smallest of the 31 EV "best eye-fits" were 8,2000; 7,488; and 7,000 cfs. The standard deviation for these 31 estimates was 322 cfs, which is only 4 percent of the average Q100.

Table 3. Plotting Paper Preferences Among 31 Eye-fitters, with Average and Range of Q100 Estimates.

	<u>Preferred Plotting Paper</u>		
	Extreme Value (EV)	Log Extreme Value (LEV)	Log Normal (LN)
Number of Students	21	6	4
Largest estimate Q100 CFS	8,200	8,500	9,200
Smallest estimates	7,000	7,200	7,400
Average of estimates	7,488	7,717	8,125
Standard deviations	322	462	846

*From observed data Walnut Gulch Watershed 63,001, USDA, 1958/77.

Fig. 8 shows one student's solution. Eye-fitting a straight line to the larger half of a flood series can also be justified because these are often large enough to behave like design sized event. Physical factors on small desert watersheds that justifying this threshold approach include: (a) any runoff-producing storms cover only part of the WS; (b) transmission losses in normally dry streambeds reduce small floods more than they do larger or piggy-back peaks; (c) some runoff is caught in stock dams.

Very little difference existed between the EV, LEV, or LN papers (statistical model) selecting selected to yield the "best eye-fits." In fact, six and four of the students selected either LEV or LN papers to be most suitable. Their average Q100 estimates exceed the average EV estimate by only 229 and 637 cfs, respectively.

Another interesting observation is that the smaller floods in the series are aligned below the larger observations in which designers have more interest. This pattern in flood frequency plots was described (24) [Potter, 1958] and became known as the "dog leg" pattern in the Bureau of Public Roads. Such smaller floods are the outcome of different hydrologic processes. In rapid credibility checks it is satisfactory to overlook these small floods and fit lines through large Q's.

An alternative computational method, which the students initially preferred, was mathematical fitting of the following arbitrarily chosen models to the entire dichotomous data set: EV, LN, LEV, LP3 with skewness computed from the station's series, and LP3 computed with a regional skewness coefficient. All analysts will get the same values for each of these mathematical Q100 estimates shown in Table 4. Notice that these range from about 5,500 to 61,000 cfs. They average 22,345 cfs, or triple the EV eye-fit. Any mathematical answer, in Table 4, is obtained without ever plotting floods. The last two estimates, of 5,541 and 17,220 cfs, are obtained by two variations of the LP3 procedure which the Bureau of the Budget tried to force upon our profession (25) [WRC, 1967].

Table 4. Results from Five Different Mathematical Models

<u>Computational Method</u>	<u>Q₁₀₀ cfs</u>
Extreme value	7,820
Log extreme value	60,873
Log normal	20,273
Log Pearson III, station series	5,541
Log Pearson III, regional	17,220
Mean of computed results	22,345
Standard deviation of results	22,407

Fortunately we are now permitted (2) [WRC, 1981] to use other distributions than LP3, when appropriate. It is incumbent upon sponsors to require that flexibility and the use of scientific judgment from contractors. Academicians must continue to probe and develop new statistical methods and ways to fit them to flood series (26) [Greis, 1983], (27) [Cunnane, 1986]. Action agencies need PC means verify in credible means even esoteric stochastic estimates.

This project could prepare a user-friendly computer graphics program to locate a series of observed floods according to Cunnane's formula on a few probability papers. Soon after an extraordinary flood occurs, action agencies need to know its significance. Eye-fitted extrapolations can rapidly guide their response. Expert interpretation of mathematically fitted distributions will follow later.

III. PRACTICAL ASPECTS OF FLOOD FREQUENCY ANALYSIS

Engineering or administrative agencies and other users of flood frequency estimates need not entirely relegate their public-safety and fiscal responsibilities to statistical models.

This colloquial section discusses some visual concepts which underlie FFA. Stochastic hydrologists have a proclivity for jargon. They must carefully qualify statements to ensure their mathematical precision. In the process, their communication with engineers, administrators and other practitioners often break down. Moreover, examination of certain postulates of the newer stochastic hydrologists did not stand up very well (28) [Kleems, 1986]. My purpose is rather to highlight some significant contributions of this mathematical branch within a broader hydrology framework.

An excellent early test (29) [Foster, 1948] was a clear expose of statistical theory applied to various hydrologic problems. Over the next 40 years many books were published: some clear others obscure, except perhaps to an elite faction known as stochastic hydrologists. Stochastic processes are defined (30) [Yevjevich, 1972] as those which treat sequences that are governed by laws of chance. A classic text (31) [Hazen, 1930] clearly explained statistical measures, graphic methods, practical examples and applications. It combined theory with practical experience. If flood frequency (FFA) is to serve society, communication must be re-opened between theoreticians and applied hydrologists.

III.1 CONFIDENCE BANDS.

A strong plea was made (32) [Chow, 1953] for using confidence bands in order to account for random variability of floods at a gage. These were called control bands in another

mathematical treatment of extremes (33) [Gumbel, 1958]. They add a safety margin to the flood frequency curve which was purely dependent on floods measured before the analysis. The classical text (34) [Benjamin & Cornell,, 1970], used in most university courses in statistical or advanced statistical hydrology, explains this range within which an estimate of Q should be expected to fall. Recent texts (35) [Haan, 1977], (36) [McCuen & Snyder, 1986] also discuss the theory and application of confidence bands around the central tendency.

For example, three sequential periods of history at one stationary gage contain different sets of floods. Consequently they produce three separate "central tendency" estimates, as shown by real data in Fig. 9. Their highest Q_{100} was 2.2 times greater than the lowest estimate. LP3 curves are very subject to such separation. One of the sub-histories produced an estimate very close to that of the 51 year record. Sensitivity to the coefficient of skewness accounts for this wide variation in the LP3 model (37) [Reich, 1976]. This is one of the causes for disappointingly high standard error of estimates (SEE) in regional flood studies.

Fig. 10 for a 172 sq. mi. Pennsylvania stream shows that the Gumbel lines, which was the original fitting technique for the EV distribution, show much less spread than do LP3 fits. Even sub-histories as long as 29-year LP3 Q_{100} 's differ by 30%. Corresponding Q_{100} 's from the Gumbel lines for the two sub-histories, G-1 and G-2, differ from each other by only 6%. In fact the 58 year EV is indistinguishable from the G-2 line.

Much of the discussion to this point may have shaken the reader's confidence in FFA. Certainly, no flood frequency line can determine a design flood with the certainty with which Newton's law of physics can determine the velocity of a free falling object. In fact, most hydrologic estimates are concerned with stochastic or random rather than deterministic processes. The engineer does, therefore, need to develop a feel for how variable estimates of the same quantity may be simply because of the particular history that had been gaged. A powerful property of statistical analysis is its ability to provide this measure of error likely in one's estimate.

Confidence bands provide a tool for expressing this important, but often neglected, aspect of FFA. Fig. 11 depicts a schematic view of the limits within which 90% of sampled frequency lines will fall (37) [Reich, 1976]. Notice how widely the outer pair of confidence bands trumpet out for 15-year records. If, however, the line had been drawn from a 50-year record, the confidence bands would have been pinched in much tighter. This quantifies how much less error central tendency estimates possess with longer gage history. In this hypothetical example, the slope of the frequency curve can be indicated by $Q_{100}/Q_{BAR} = 4.2$. Q_{BAR} is the average of the annual maximum flood series. Moreover, the coefficient of variation (CVQ) which is also used in Chow's calculation of these confidence curves, was chosen as 1 in our example.

Where stationarity permits analysts to use the entire record to estimate the "central tendency" estimate, marked with an

arrowhead in Fig. 11, is generally used. Chow and others facilitated the mathematical fitting of confidence bands around the central tendency. The solid curves are closer to the central tendency because they represent a 50-year period of record. This example shows that 90% of estimates will lie within the two curves. 5% above the upper (95%) curve, and 5% below the lower curve. The outer dotted lines show how far apart confidence bands spread if the same central tendency had been established from a 15 year record.

III.1.1 STATE SPECIFIED CONFIDENCE LEVELS WORTH CONSIDERATION.

Stochastic hydrologists have done an admirable job of developing confidence band methods. Clear descriptions of their applications have been widely published. Considering that safety factors as large as 2 are common in structural engineering. It is difficult to understand why hydraulic engineers do not use anything greater than the central tendency for flood estimates. Designing bridges or community flood protection with central tendency accepts the 50% chance that floods will be higher or lower. Structural engineers act very differently when life and property are concerned. Many well-instrumented, replicated, laboratory, tests-to-failure of concrete beams or metal bars preceded the structural engineering practice. Even after reviewing such reliable data, those engineers apply safety factors as large as 2 to their designs. Hydraulic engineers have far less knowledge future floods on gaged or ungaged rivers.

They use central tendency estimates, without multiplying by any safety factor.

Serious consideration should soon be given at the State level to confidence bands. For instance, one decision could be made to raise a flood estimate to the 95% confidence band if life and high damage potential exists. In another situation where only short traffic delays and minor repairs may result from another flood, the design could be assigned to a different class allowing a design flood closer to the central tendency estimate. Say at the 80% confidence level.

In 1977 & 1979 Pima County and the City of Tucson, who provided 50% matching funds for the USGS flood study program, unsuccessfully requested them to use a confidence limit approach rather than central tendency. In 1982 during another USGS Cooperative small watershed project Pima County withdrew, presumably because of disenchantment.

III.2 USGS CONTRIBUTIONS

The United States Geological Survey (USGS) has experts in both stochastic and conventional hydrology. Their Tucson office has historically been responsible for very fine publications. An excellent national summary, including our neighboring States, was delivered to the Transportation Research Board's meeting (38) [Thomas, 1987]. It listed 64 reports on estimating flood-peak discharges using watershed and climatic characteristics, throughout the past decade. These are typically prepared in

nationwide District Offices with expert assistance and software from National Center, VA.

For the last two decades the agency was plagued by the Water Resources Council's arbitrary choice of LP3. LP3 is still under fire from many USGS and other (39) [Matalas, Slack & Wallis, 1975] experts here and abroad. Fig. 12 shows, for a pristine Arizona watershed, how poorly the LP3 curve represents observations. Application of sample skewness to the 30 years station data produces a Q100 of about 4,500 cfs. If the regional modification were applied, this 82 square mile Q100 becomes about 22,000cfs. An eye-fit through the biggest half or two-third of observed maxima suggests 10,000 cfs.

The 1981 Water Resources Council (WRC) guidelines now releases government agencies from slavishly applying LP3 where "special situations may require other approaches." Unshackled from LP3, the USGS could enter less noisy station estimates of Q100 or other flood estimates as dependent variables into future multiple regression analysis. Their National Center's strength in regional regression and other advanced approaches could hopefully reduce the standard error of estimate for ungaged watersheds. This is the final product that the highway engineer is interested in.

III.3 ARS WALNUT GULCH DATA AND RESEARCH.

Tucson is indeed fortunate to have been the home of the Southwest Rangeland Watershed Research Center for thirty years. Their senior staff are Adjunct Professors at the University and

have supervised many graduate students in surface water investigations. They have made substantial contributions to the understanding of desert region floods. Local government received excellent cooperation and goodwill from these U.S. Department of Agriculture personnel. There is a need to translate their scientific publications for practical application to highway drainage design elsewhere.

One center on which this ARS research is focused is on Walnut Gulch and its tributaries near Tombstone, Cochise County. Its chihuahuan desert scrub and semidesert grassland ecotypes are common to other parts of southern Arizona. Their intensity-duration-frequency relationships for short storms on their experimental areas are virtually identical to those at Tucson's International Airport.

III.4 STATE SHOULD BOOST GAGED URBAN WATERSHEDS

The high growth rate mentioned in the first paragraph of the EXECUTIVE SUMMARY require mention of a most important need for highway drainage knowledge. Almost all of the stream gages referred to above were draining primarily rural watersheds. Yet population growth dictates that the greatest expenditure on highway drainage structures will involve small watersheds which will be in urban watersheds. Now is the time to establish rainfall/runoff recording systems to acquire information needed two decades hence. Arizona has some precedents on which to build a sounder future.

Tucson does have some pre-flood-warning rainfall recorders and corresponding water stage recorders. The first were established by Dr. Sol Resnick, retired of the Water Resources Research Center, University of Arizona. Unfortunately, students may not have been the best operators or data processors. Neither the USGS nor Pima County Flood Control District were interested in taking the gages over for modernization. Funds cannot be found at the University to maintain them, much less to update with state of the art equipment. Instead of the three watersheds of 1 to 2 3/4 sq. mi. there is really a need for four times as many, concentrating on smaller source areas.

The USGS is operating eight instrumented Tucson watersheds between 1/2 and 10 sq. mi. Four of these average about 20-year records, and three less than 10 years. This network grew by cooperation among city, county and federal governments. As alluded to before, disagreements caused a cutback to partial-year operation. At last reporting the USGS were looking forward to termination.

Both of these urban streamgaging networks would have allowed the calibration of humid-area urban hydrographs for anywhere in Arizona. The only message is that if these needed model calibration are to be made, State government will have to make a 20 to 30 year commitment. They can provide multiple benefits, including groundwater pollution from street runoff which recharges our aquifers close to the consumers. Flood hydrograph models validated in Tucson, can be applied to urban or developing watersheds anywhere in Arizona. The outcome may show that the

means by which our urban areas are drained produce hydrographs that differ vastly from the national computer models that are used in urban USA.

IV. CONCLUSIONS

Considering additional data and knowledge available since the preparation of previous ADOT flood frequency manuals, a very good chance exists for substantial improvements to be made in such manuals. An adequate network of data and experts exist to maximize the interactions from the multiple disciplines associated with regional flood frequency analysis. Naturally the Arizona study will utilize readily available flood data from neighboring portions of eastern California, southeastern Nevada, southern Utah, and western New Mexico. Involvements with statewide programs throughout those four states may dilute and delay the effort required to expedite Arizona's study.

The following highlights should be enumerated:

1. The last two work products will require 36 months for completion. A statewide report on flood changes could be available in 15 months. Acompendium of at-gage flood tabulations of raw data, chronological plots, and ranked data points plotted along with the selected flood frequency curve will be available after 18 months.
2. The application of new analytical techniques to a data-base, which increased by 15 years, will reduce standard errors of estimate.

3. Equations relating flood estimates like Q_{100} , or parameters like Q_{BAR} or the coefficient of variation, will be sought separately for large unregulated watersheds, intermediate sized streams, and watersheds smaller than about 5 or 10 sq. mi.. Meteorological and geomorphic aspects will be considered.
4. Improvement of flood frequency estimates will gain from the new rainfall intensity duration frequency atlas for Arizona. Without the latter, relationships will probable not be quantified between floods and this causative factor. Moreover, application to most design sites within Arizona will give very faulty small-area or pavement discharges. Under-prediction are expected to be most common, and often by many times.
5. Examination of hydrographs and storms measured at experimental watersheds will add a new dimension to Arizona Flood Frequency Manuals. This may confirm an entirely new personal computer means of predicting floods on small ungaged watersheds.

REFERENCES

1. Roeske, R.H., "Method for Estimating the Magnitude and Frequency of Floods in Arizona," Report No. ADOT-RS-15-121, by U.S. Geological Survey, Tucson, 82 p., 1978.
2. Water Resources Council, Hydrology Committee, "Guidelines for Determining Flood Flow Frequency," Bulletin 17B, 183 p., 1982
3. Pilon, P.J. Condie, R., & Harvey, K.D., "Consolidated Frequency Analysis Package (CFA) User Manual for Version 1 - DEC PRO Series," Water Resources Branch, Inland Waters Directorate, Environment Canada, Ottawa, Ontario, K1A OE7, pp. 148, 1985.
4. Eychaner, J.A., "Estimation of Magnitude and Frequency of Floods in Pima County, Arizona, With Comparisons of Alternative Methods," USGS, Water Resources 26 Investigations Report 84-4142, 69 p., August 1984.
5. Wahl, J., "Flood Prediction Procedures for Ungaged Arid Watersheds in Southwestern United States," USGS, Prospectus delivered at Tri-regional Hydraulics Conference, of FHWA, 24, p., June 1987.
6. Reich, B.M., & Davis D.P., "Estimating the Regulatory Flood on a Defrading River," Proc. International Symp. Flood Frequency & Risk Analysis, Baton Rouge, LA. 17 p., 1986.
7. Reich, B.M., "Effect of Floodplain Erosion on Flood Probability," Proceedings of U.S.-China Bilateral Symposium on the Analysis of Extraordinary Flood Events," Nanjing, 23 p., Oct. 1985.
8. Reich, B.M., & de Roulhac, D.G., "Microcomputer Graphics Flood Stationarity Test," Pre-print ASCE, HY Div., HY 8 Hydrology in the Small Computer Age, Lake Buena Vista, FL, p. 1401-1406, 1985.
9. Reich, B.M., King, Y.P., & White, E.L., "Flood Peak Frequency Design Manual." Interim Report to Pa. Dept. of Transportation, 6 p., Feb, 1971.
10. Aron, G., Kibler, D.F., White, E.L., et al., "Field Manual of Procedure PSU-IV for Estimating Design Flood Peaks on Ungaged Pennsylvania Watersheds." The Pennsylvania State University, Dept. of Civil Engineering, 37 p., 1981.
11. Morton, Michael R., "Analysis and Mapping of Pennsylvania Streamflow Statistics and Testing of Empirical Flood Peak

Estimating Methods," The Pennsylvania State University, Civil Engineering, M.S. Thesis, 161 p., 1981.

12. Tasker, G.D., Eychaner, J.H., & Stedinger, J.R., "Application of Generalized Least Squares in Regional Hydrologic Regression Analysis," Manuscript for publication as Water Supply Paper, USGS, 27 p., 1987.
13. Reich, B.M., "Additional Analysis of Flood Data In and Around Pima County to Supplement Recent USGS Efforts to Establish Regional Relationships to be Used in Flood Insurance Studies," Report to City of Tucson, and USGS; by Pima County Department of Transportation, 21 pp., August 1978.
14. Reich, B.M., & Renard, K.G., "Application of Advances in Flood Frequency Analysis," Water Resources Bulletin, Vol. 17, No. 1:67-74, 1981.
15. Guisti, E.V., "Distribution of River Basin Areas in the Conterminous United States," Int. Ass. of Sc. Hydrology, Gentbrugge, Belgique, Vol. VII, No. 3, p. 20-29, 1963.
16. Hirschboeck, K.K., "Hydroclimatically-Defined Mixed Distributions in Partial Duration Flood Series," International Symposium on Flood Frequency and Risk Analysis, Louisiana State University, 11 pp., 1986.
17. Miller, J.F., Frederick, R.H., & Tracy, R.J., "Precipitation-Frequency Atlas of the Western United States, NOAA Atlas 2, U.S. Dept. of Commerce, Silver Spring, MD., 41 p., 1973.
18. Reich, B.M., Brazel, A.J., & Clark, R.A., "State-of-the-Art-Study: Storm Rainfall Atlas for Arizona," AZ. Dept. of Transportation Report.FHWA/AZ-87/276, 103c p., July 1987.
19. Woolhiser, D.A., "Sensitivity of Calculated Peak Runoff Rates to Rainfall Sampling Frequency," Proc. 2nd Scientific Assemble, International Association of Sc. Hydrology, 12p., 1986.
20. Reich, B.M., "Flood Series for Gaged Pennsylvania Streams," Inst. for Research on Land & Water Resources, The Pennsylvania State University, Publ. 63, 83., Dec. 1969.
21. de Roulhac, D.G., "Application of Computer Graphics in the Selection of Rainfall Frequency Models for Environmental Engineering," M.S. Thesis, Dept. of Civil Engineering, University of Arizona, 106 p., 1987.
22. Reich, B.M., "Man Outmatches Math Models for Flood Frequency," Public Works, pp. 56-57, July 1980.

23. Cunneane, C., "Unbiased Plotting Positions--A Review." Journ. of Hydrology, Vol. 37 3:205-222, 1978.
24. Potter, W.D., "Upper and Lower Frequency Curves for Peak Rates of Runoff," Trans. Am. Geophysical Union, Vol. 39(1) p. 100-105 1958.
25. Water Resources Council, Hydrology Committee, "A Uniform Technique for Determining Flood Flow Frequencies," Bulletin 15, 15 p., 1967.
26. Greis, N.P., "Flood Frequency Analysis: A Review of 1979-1982," Reviews of Geophysical & Space Physics, Vol. 21, No. 3, p. 699-706, 1983.
27. Cunneane, C., "Review of Statistical Models for Flood Frequency Estimation," Keynote Paper, International Symposium on Flood Frequency and Risk Analysis, Baton Rouge, U.S.A. 51, p., 1986.
28. Klems, V., "Hydrological and Engineering Relevance of Flood Frequency Analysis," Proc. International Symposium on Flood Frequency and Risk Analysis, Louisiana State University, 20 pp., 1986.
29. Foster, E.E., "Rainfall and Runoff," The Macmillan Co., 487 p., 1948.
30. Yevjevich, V., "Stochastic Processes in Hydrology," Water Resources Publications 276 p. 1972.
31. Hazen, A., "Flood Flows: A Study of Frequencies and Magnitudes," John Wiley & Sons, Inc., N.Y., 199 p., 1930.
32. Chow, V.T., "Frequency Analysis of Hydrologic Data with Special Application to Rainfall Intensities," University of Illinois, Engineering Experiment Station Bulletin No. 414, 80., 1953.
33. Gumbel, E.J., "Statistics of Extremes," Columbia University Press, 375 p., 1958.
34. Benjamin, J.R., & Cornell, C.A., "Probability, Statistics and Decision for Civil Engineers," McGraw-Hill Book Co., 684 p., 1970.
35. Haan, C.T., "Statistical Methods in Hydrology," The Iowa State University Press, 378 p., 1977.
36. McCuen, R.H. & Snyder, W.M., "Hydrologic Modeling: Statistical Methods and Applications," Prentice-Hall, 568 p., 1986.

37. Reich, B.M., "Magnitude and Frequency of Floods," CRC Critical Reviews in Environmental Control," Vol. 6, No. 4, p. 297-348, 1976.
38. Thomas, W.O., Jr., "Summary of U.S. Geological Survey Regional Regression Equations," presented to Transportation Research Board, 22 pp., Jan. 1987.
39. Matalas, N.C., Slack, J.R., Wallis, J.R., "Regional Skew in Search of a Parent," Water Resources Research, Vol. 11, No. 6: 815-826, 1975.

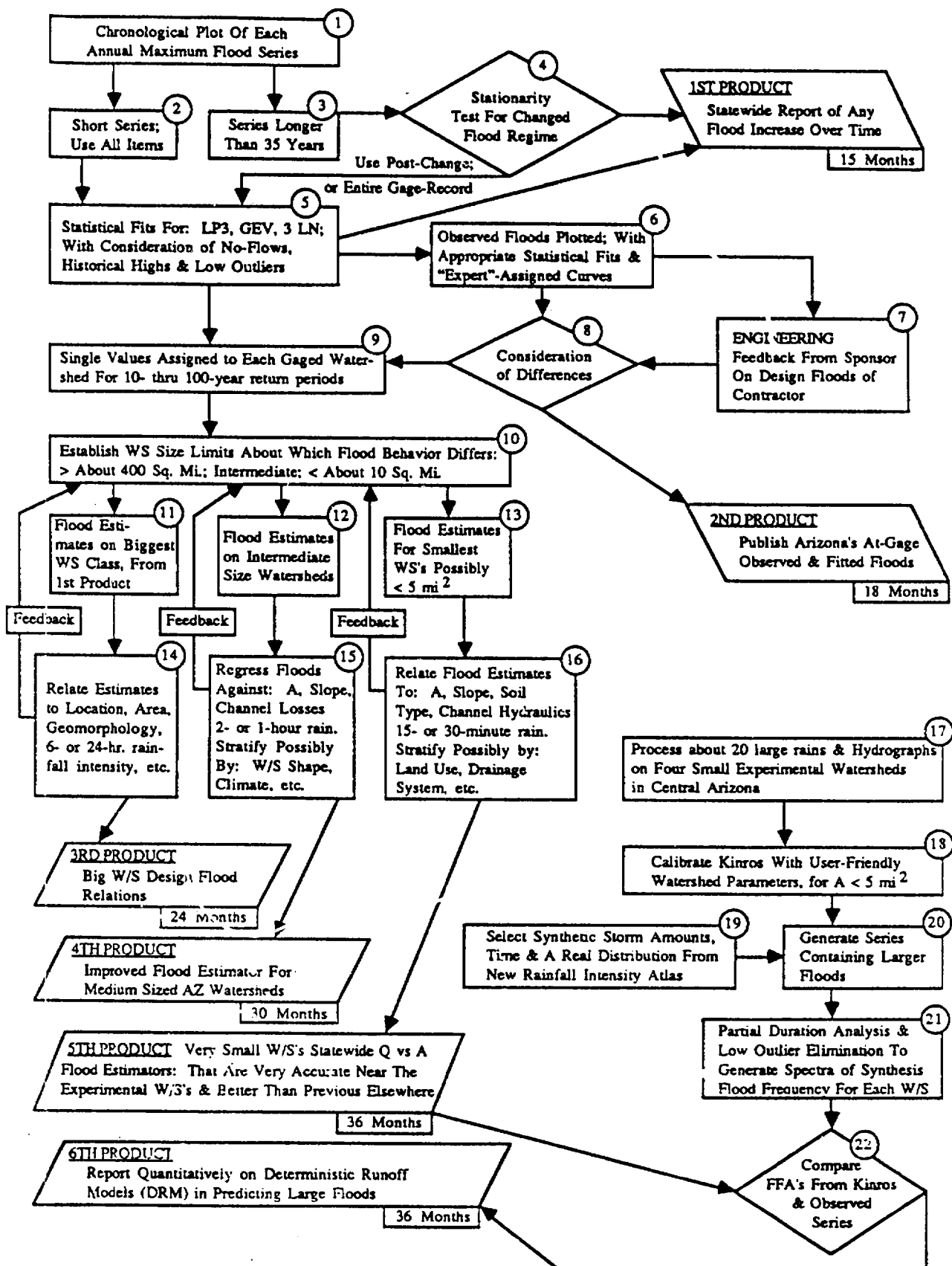


Figure 1
Flowchart of Research Tasks & Delivery Schedule for 6 Workproducts

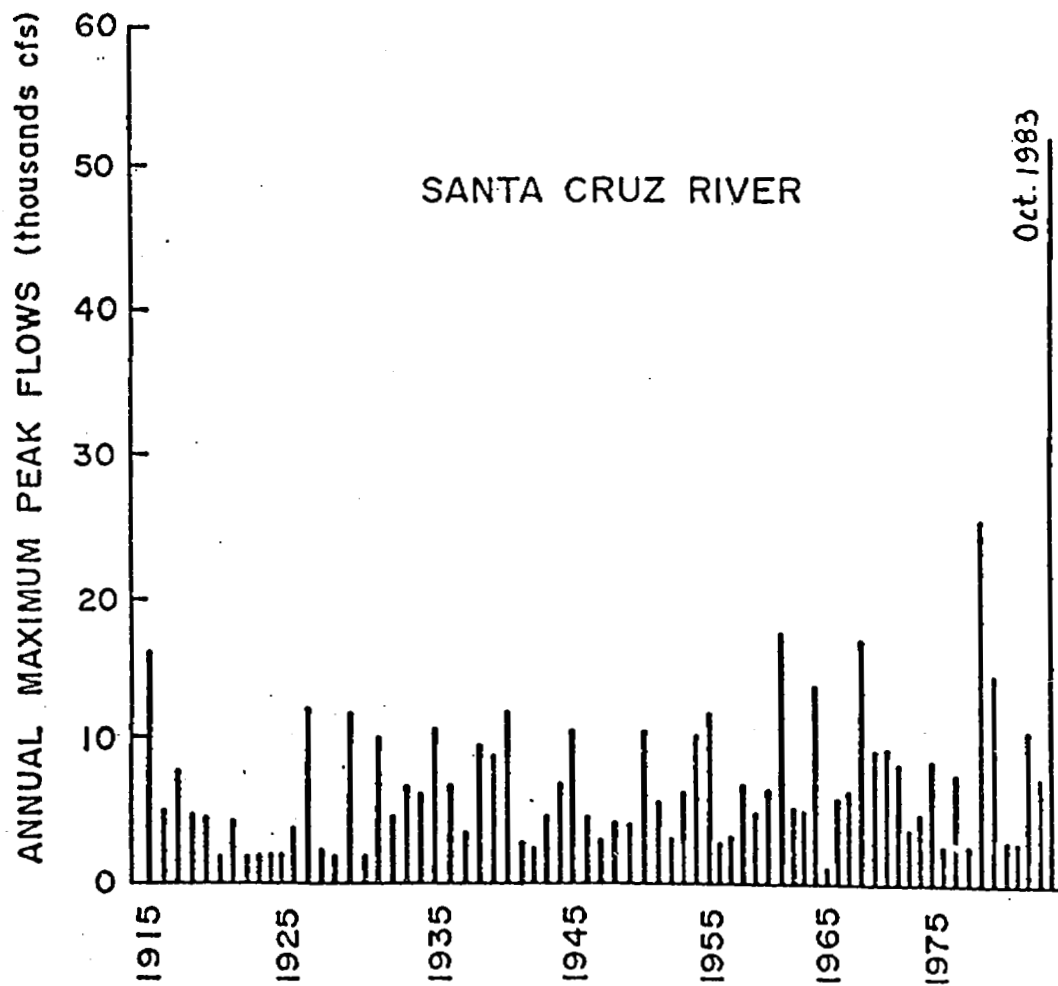


Fig. 2. Chronological Series of Floods Observed at Congress Street

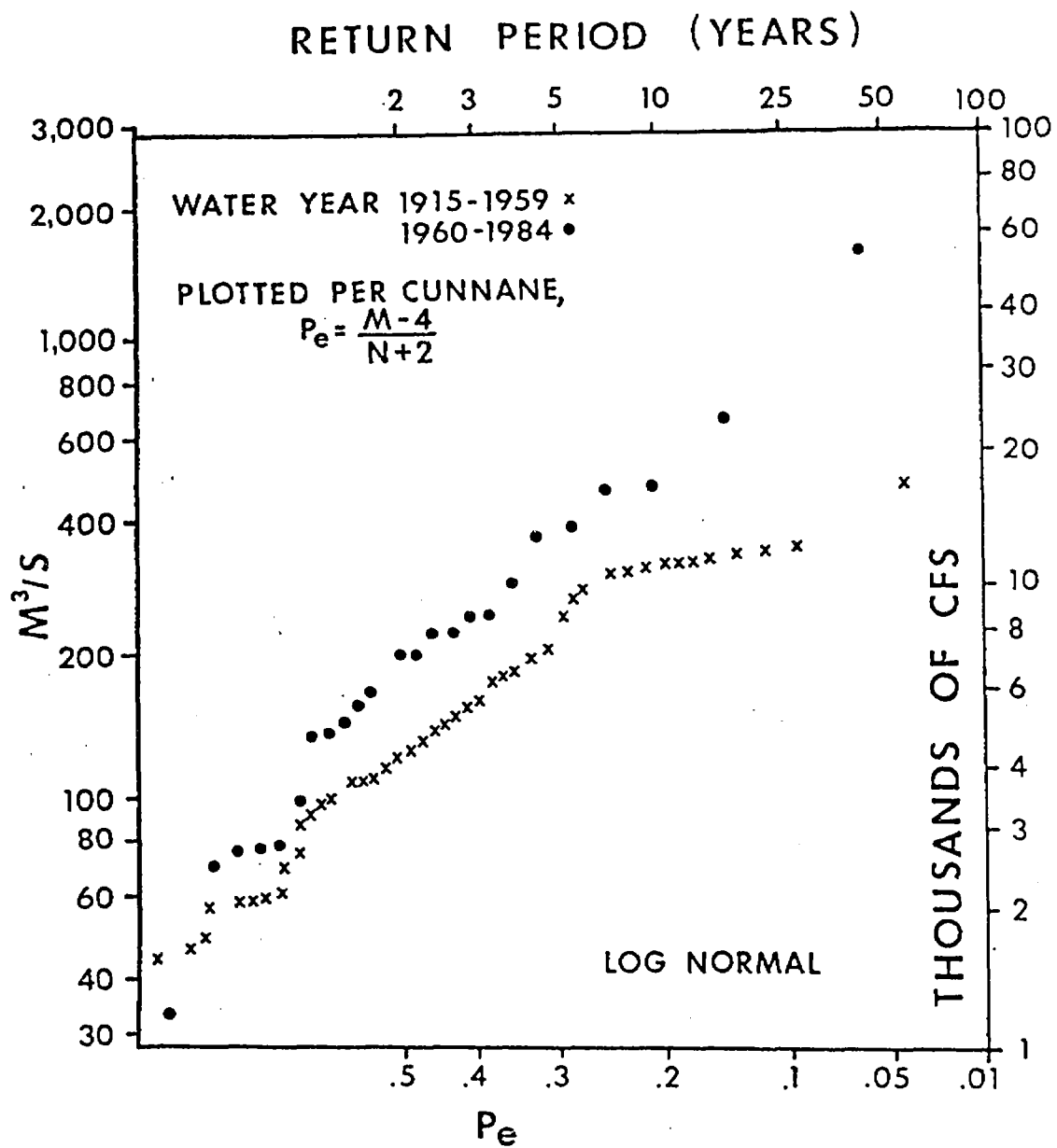


Fig. 3. Graphical Non-stationarity Test Shows: Floods in Recent 25 Years Are Far Bigger Than Those in the Earlier Record

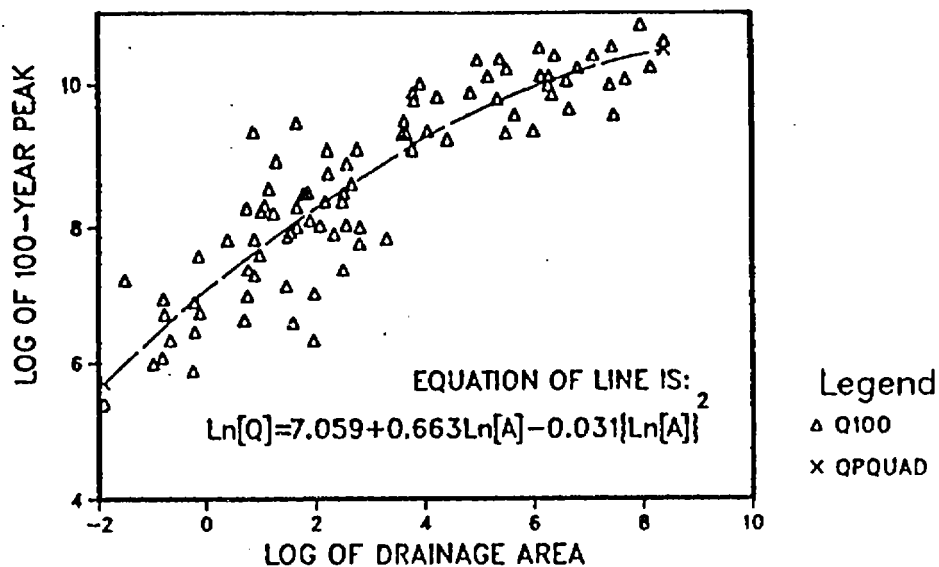


Fig. 4. Scatter of PL3-Q100's, in Log Units. After USGS Applied 1987 Stochastic Methods to Watersheds In/ Around Pima County

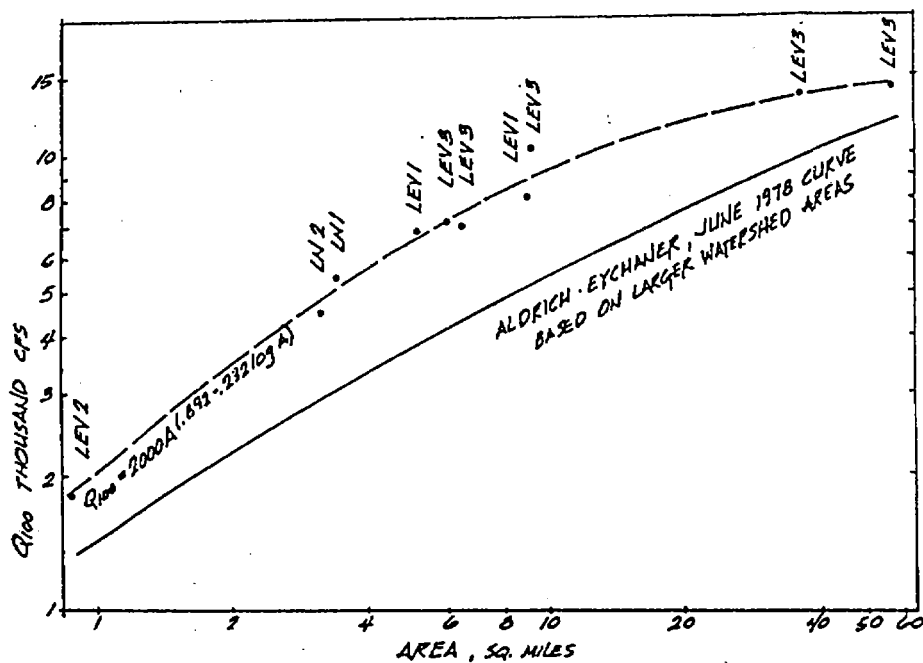


Fig. 5. Tight Regression Between A and "Best Eye-Fit" Q100 On 10 Small WG Watershed and Its Relationship to USGS Q vs A Curve from 49 Sites of All Sizes Throughout a Larger Region

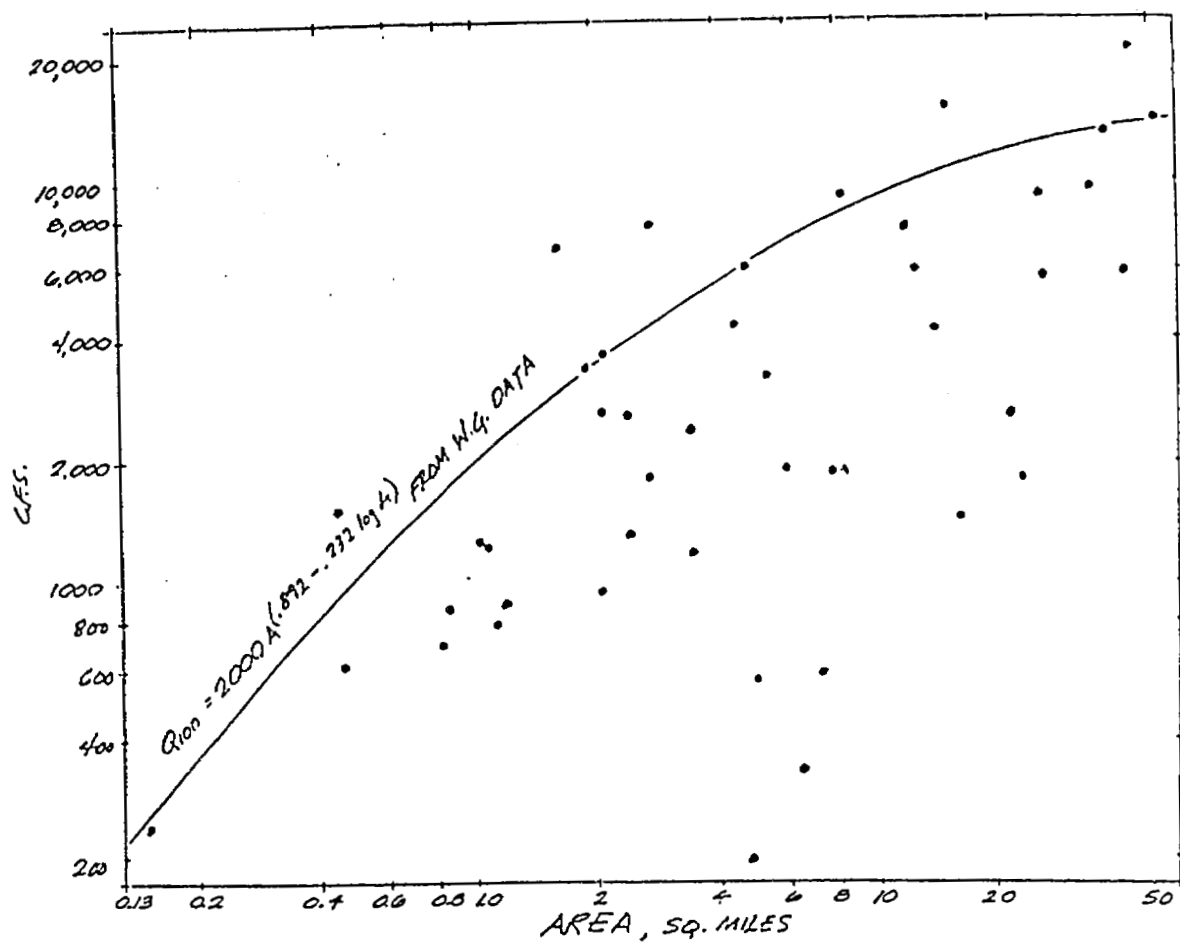


Fig. 6. Scatter of Pima County "Best Eye-fit" Q100 From 48 USGS Gaged Watersheds Spread Throughout S.E.AZ

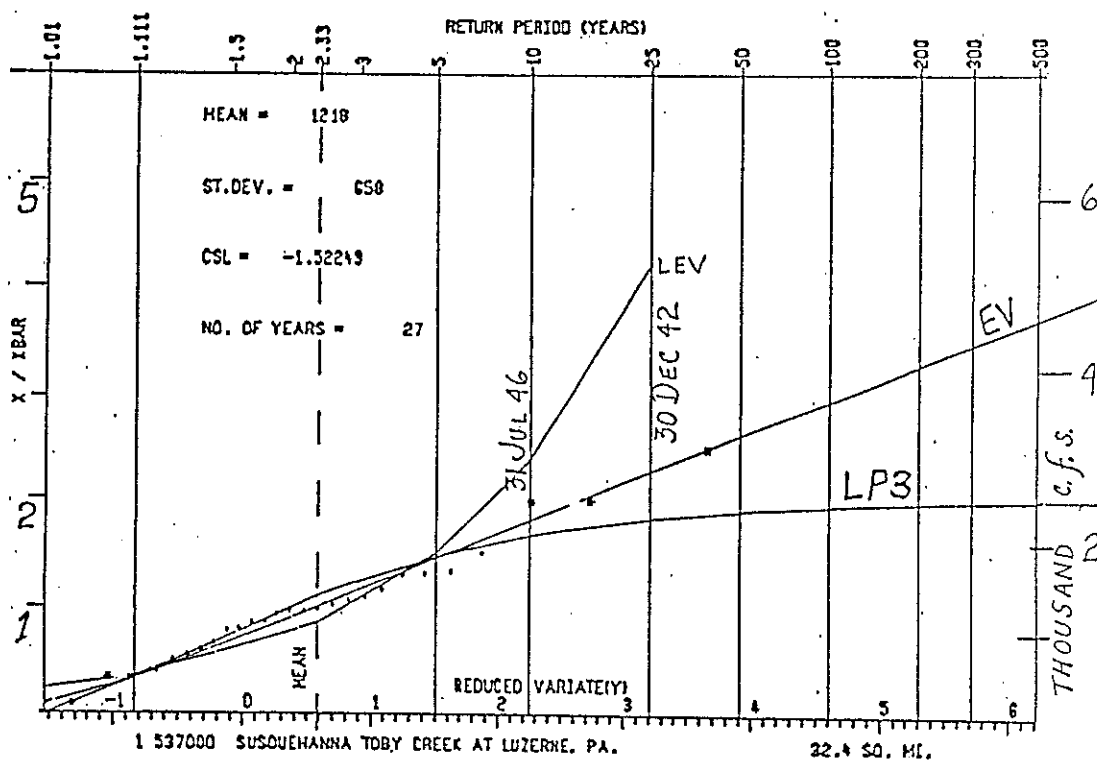
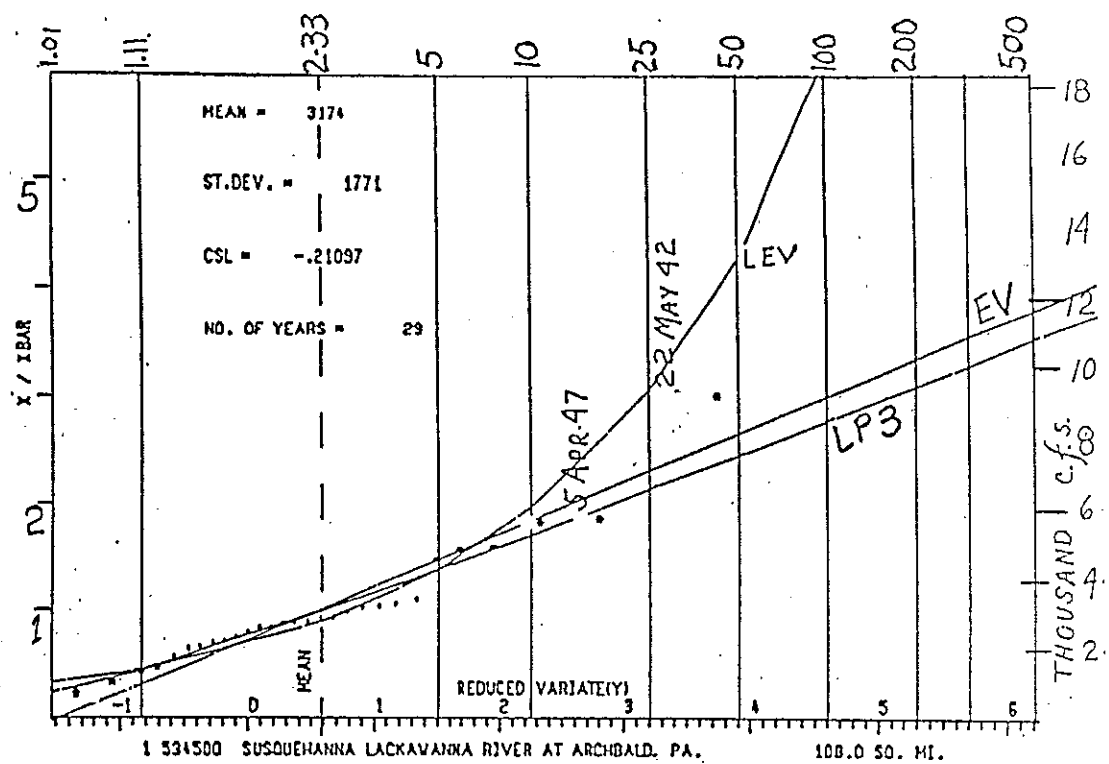


Fig. 7. Twenty-year Old Example of Graphical FFA's That Informed Users How Differently Individual Streams Were Computed By Various Statistical Distributions

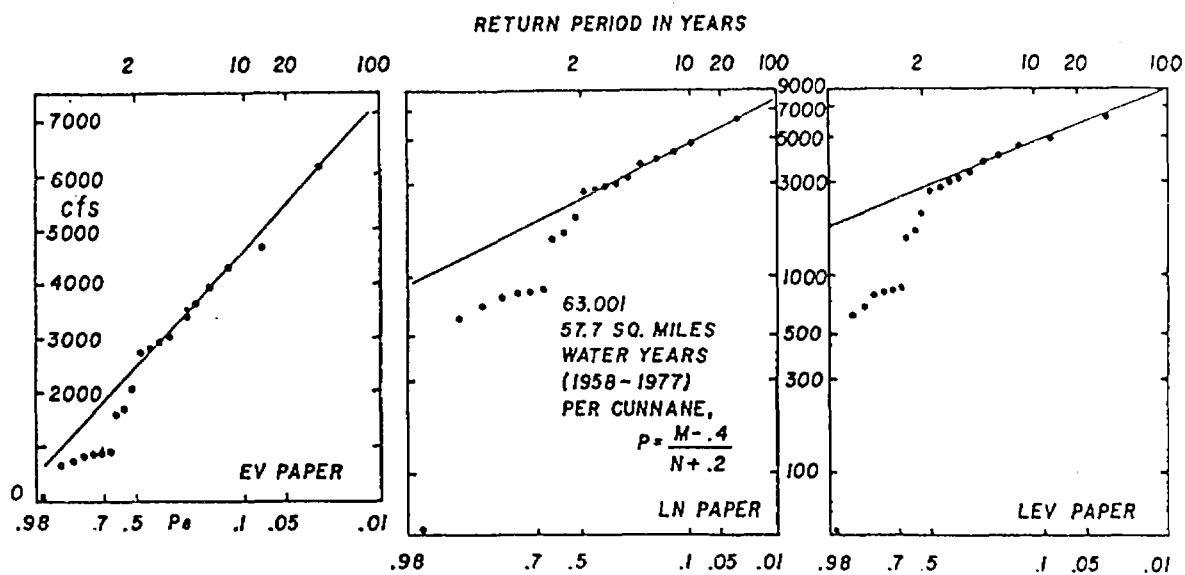


Fig. 8. Flood Series Plotted on Three Probability Papers, & One Student's "Best Eye-fits" to Determine Q100

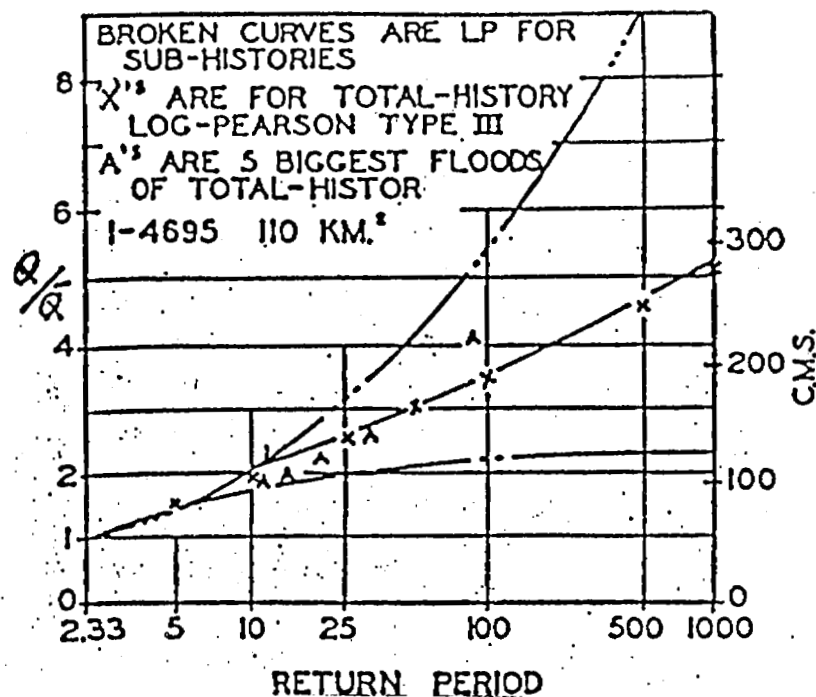


Fig. 9. Example of Widely Separate LP3 Curves from Three 17-year Segments of a 42 sq. mi. WS

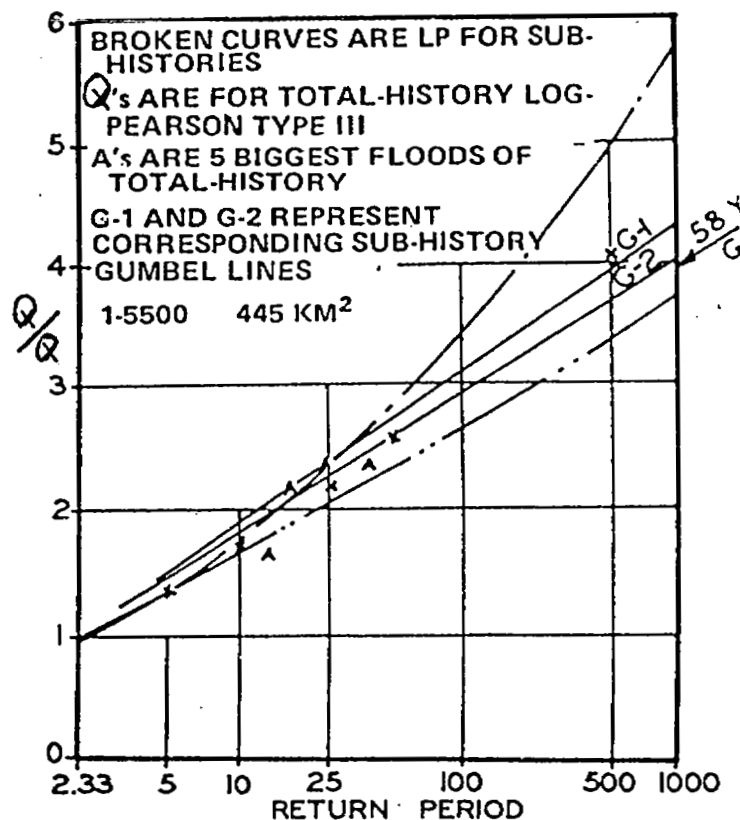


Fig. 10. Spread Between Flood Estimates from Two 29-year Segments was Smaller With Gumbel's EV Than With LP3 Mathematical Fitting

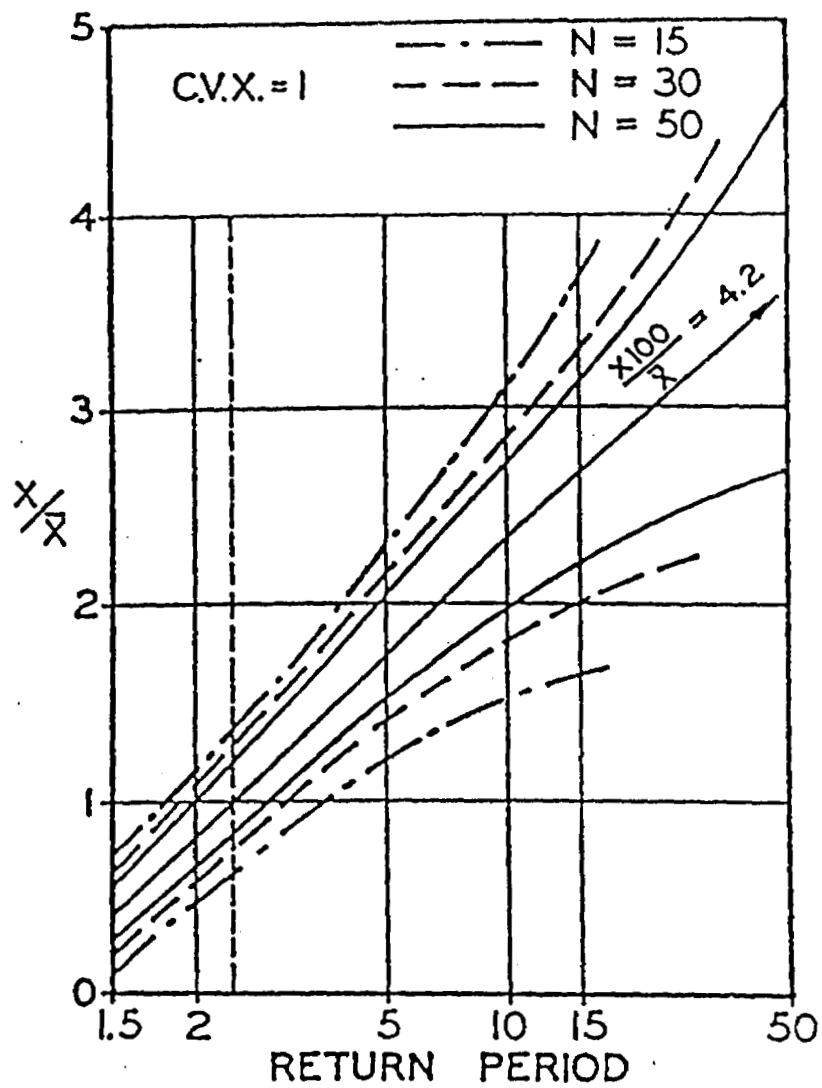


Fig. 11. Hypothetical Example of Chow's Confidence Bands About EV Central Tendency

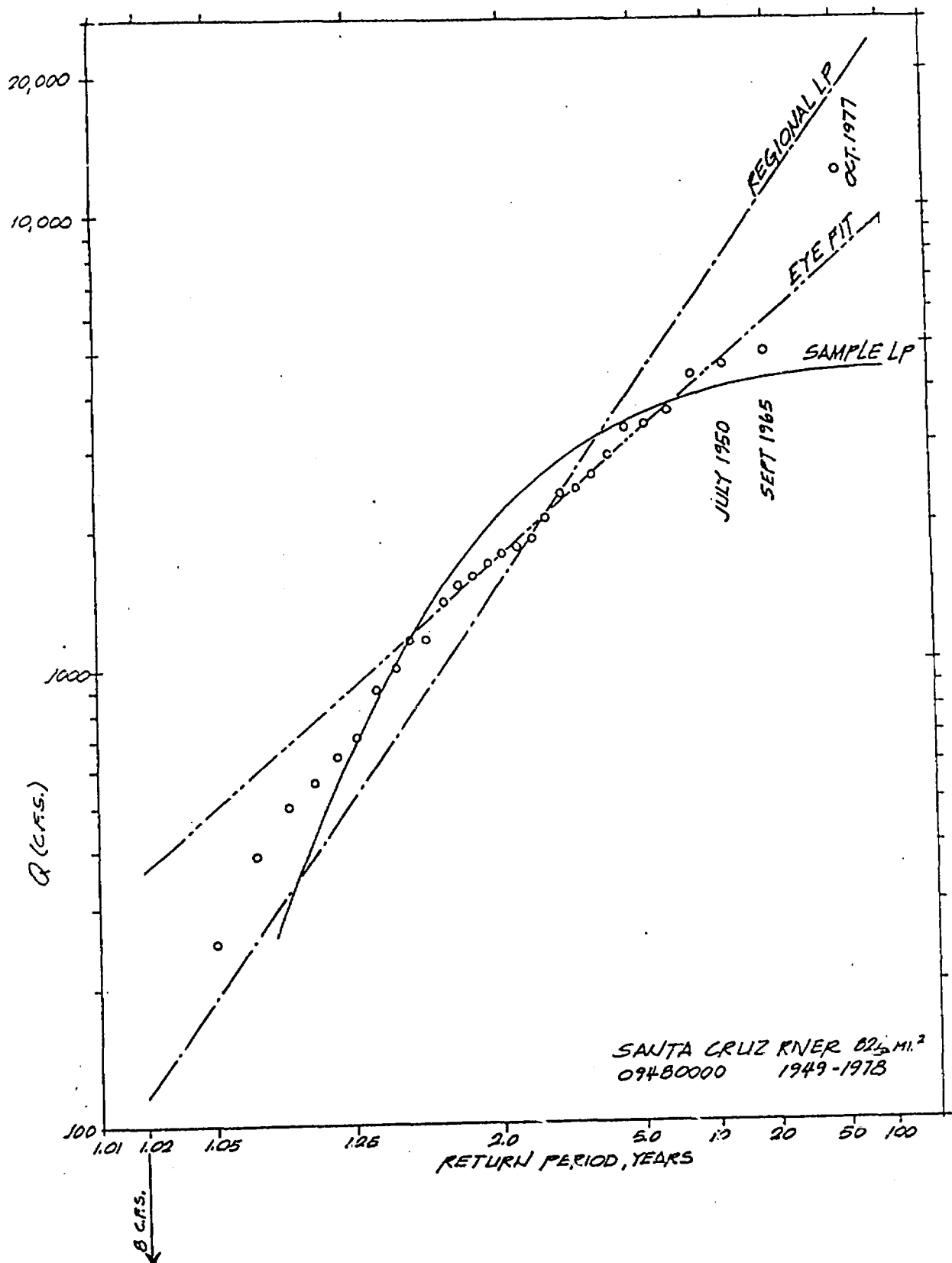


Fig. 12. Computer Output from LP3 Give Strange Estimates if Outlier or Regional Skew Problems Arise